

PB88-102751

Background for the Synthesis and
Integration of Forest Response to
Atmospheric Deposition

(U.S.) Corvallis Environmental Research Lab., OR

Sep 87



EPA/600/D-87/266
September 1987

BACKGROUND FOR THE SYNTHESIS AND
INTEGRATION OF FOREST RESPONSE TO
ATMOSPHERIC DEPOSITION

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TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)		
1. REPORT NO. EPA/600/D-87/266	2.	3. RECIPIENT'S ACCESSION NO. PB88-102751
4. TITLE AND SUBTITLE Background for the Synthesis and Integration of Forest Response to Atmospheric Deposition	5. REPORT DATE September 1987	
	6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) S. Ross Kiester	8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS US EPA, ERL-Corvallis	10. PROGRAM ELEMENT NO.	
	11. CONTRACT/GRANT NO.	
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Corvallis, OR 97333	13. TYPE OF REPORT AND PERIOD COVERED Symposium Paper	
	14. SPONSORING AGENCY CODE EPA 600/02	
15. SUPPLEMENTARY NOTES		
16. ABSTRACT This paper is based on a project entitled A Review of the Statistical Methods for the Evaluation of Atmospheric Deposition Influences on Forests (ADIF/STAT). Because statistics consist of the studies of the general methods of inference for scientific research, thorough presentation must encompass an understanding of the entire scientific problem as well as the statistical methods used to evaluate the problem. Therefore, we have considered the general conceptual basis of the research, problems of experimental design, and problems of interpretation, as well as statistical methods. In particular, we are attempting to understand the relationship between studies of atmospheric deposition and the general problems of forest ecology. To understand a complex ecological problem such as the effect of atmospheric deposition on forests requires diverse approaches. Diverse studies using different approaches need to be funded. Pilot studies need to be developed to help in the design of long-term monitoring studies, to screen for variables, and to estimate efficient sampling intensities. Statistical analyses of both short and long-term effects of climate and weather on forests and trees need to proceed.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 28
	20. SECURITY CLASS (This page) Unclassified	22. PRICE A82 9.95

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BACKGROUND FOR THE SYNTHESIS AND INTEGRATION OF FOREST RESPONSE TO ATMOSPHERIC DEPOSITION

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INTRODUCTION

Concern about the potential effects of atmospheric deposition on forests is derived from three sources. The first is the apparent effect of atmospheric deposition on some aquatic systems. The second, considered a possible leading indicator of what could happen in the United States, is the effect of atmospheric deposition on European forests. The third source is a small number of published and unpublished studies which claim to show an overall reduction in growth of some forests in the eastern and southeastern states.

The National Acid Precipitation Assessment Program (NAPAP) Section V (Terrestrial Systems) has developed a joint program between the Environmental Protection Agency (EPA) and the U.S. Forest Service. This joint program, called the Forest Response Program, conducts numerous studies on aspects of the relationship between atmospheric deposition and forest condition.

This paper is based on a project entitled *A Review of the Statistical Methods for the Evaluation of Atmospheric Deposition Influences on Forests* (ADIF/STAT). Because statistics consist of the studies of the general methods of inference for scientific research, thorough presentation must encompass an understanding of the entire scientific problem as well as the statistical methods used to evaluate the problem. Therefore, we have considered the general conceptual basis of the research, problems of experimental design, and problems of interpretation, as well as statistical methods. In particular, we are attempting to understand the relationship between studies of atmospheric deposition and the general problems of forest ecology.

Summary

To understand a complex ecological problem such as the effect of atmospheric deposition on forests requires diverse approaches. Diverse studies using different approaches need to be funded. The use of statistical methods limits the ability to quantify the effect (Ware and Louis 1983). New methods need to be developed for analyses of growth patterns especially in situations where early inadequate statistical methods caused some people to abandon the approach altogether.

Pilot studies need to be developed to help in the design of long-term monitoring studies, to screen for variables, and to estimate efficient sampling intensities. Models of tree and stand dynamics must be constructed to estimate the forest-wide effect of a particular cause and effect mechanism, to provide a null model, and to aid in risk assessment and forest valuation.

Statistical analyses of both short and long-term effects of climate and weather on forests and trees need to proceed. Such natural factors greatly affect the process of atmospheric deposition. However, it is imperative that this effort be directed at the effect on forests not just general climatic modeling.

Three Obiter Dicta

1. Research on the effects of atmospheric deposition on forest condition is difficult and complex. Because of the importance of this research, the quality of the research must be superior.
2. Successful analysis of this problem will require state-of-the-art statistical methods and development of new methods. Statistical methods, as well as atmospheric deposition research, are evolving sciences. As such, they will require care in development and interpretation.
3. The scientist or administrator must be aware of the distinction between scientific understanding and risk assessment. This vigilance is especially necessary in this case because risk assessment will have to proceed in the absence of complete scientific understanding. Particular statistical methods have been developed specifically for use in risk assessment and these should be distinguished from the more usual methods used in scientific inference.

ECOLOGICAL FOUNDATION OF ATMOSPHERIC DEPOSITION RESEARCH

Variation is the central concern of evolutionary biology. In ecology the variation occurs as a complex of interactions. Thus the warnings from the study of evolution must be heeded: Multiple causes and multiple effects are the rule, not the exception. In particular, necessity and sufficiency must not be confused with causation. Most ecological causes are neither necessary nor sufficient for their effects. For example, smoking is neither a necessary nor a sufficient condition for lung cancer. Many people who smoke do not get lung cancer and some people who get lung cancer do not smoke. However, there is a clear pattern of causation (Hull 1974).

Because of the complexity of ecological systems, we must be aware of the limits to our ability to understand them. In particular, when considering models of ecosystems, it may be useful to recall the argument of Richard Levins (1966) that no single model in ecology can simultaneously maximize the three desiderata of reality, generality, and precision. It appears to be an empirical fact that we can only achieve two of these in any one model. Which one we sacrifice depends upon our research methods and on the purpose of the research.

This leads to an important dilemma in atmospheric deposition research. We need reality and precision in our understanding to make accurate assessments of the impact of atmospheric deposition on particular forest systems. However, this implies the sacrifice of generality. Two problems arise from this.

First, it creates an intellectual frustration for the scientist who wishes to search for general laws and patterns. It also creates administrative frustration in that decisions to act in one region cannot necessarily be based on situations in nearby regions.

Second, from a statistical point of view, our sample sizes are smaller than we would use for generalized studies. If two geographic areas are subject to the same patterns of causation, we could consider them replicates. However, the complexity of the forest ecosystem may force us to consider them as different systems.

Will atmospheric deposition research simply be reduced to a series of case studies? This is a historic problem in forestry research. As G.W.S. Trow (1984) phrases it, forestry is somewhere; whereas science is everywhere and nowhere. Thus, specific forests must be considered at particular times to achieve the understanding a forester needs. In contrast, a scientist may consider any forest as an example of how forests function. In forestry the general does not contain the particular.

CONCEPT OF FOREST CONDITION

The concept of forest condition lies at the beginning of any atmospheric deposition research. Yet, this concept is perhaps the most elusive of all. From the forest ecology perspective, there is no natural concept of condition. Condition is not a property of forests the way atomic weight is a property of an element. Condition is a human interpretation placed on the forest in the presence of a complex human context. Thus there are a large number of measures of forest condition. Even the classification of the possible forms of forest is not clear. However, they include indicies, symptoms, bioassays, and dynamic properties at several levels.

Condition measures may be properties of both individuals and ensembles of trees, stands, and forests. Biomass, timber volume, growth, reproduction, diversity, evenness, frequency of rare species, foliar damage, crown dieback, stability, persistence, and resilience all apply to one or more of these groups.

Forest condition is a subjective evaluation similar to the judgment a forester makes in determining the level that a forest is stocked. Ideally, we would prefer to have baseline data on forest study sites before there was any atmospheric deposition. This would provide an index for assessing the impact of atmospheric deposition. Different researchers will do this in different ways. The ecologist thinks of reproduction, while the forester thinks of measuring radial or basal area growth. In Germany, the state of *Waldsterben* has been quantified by categorizing trees as to crown vigor.

Apart from the obvious problems of choosing the measure by which to quantify the forest condition, there are some statistical issues which should be considered. Objective measures (i.e., radial increment) may have utility if the variation in their changes can be explained in a valid statistical manner. Subjective measures (i.e., observer ratings of crown vigor) result in variability among observers and observer awareness. For example, a Frazer fir on Mount Mitchell may appear healthy to one observer but sickly to another scientist who recognizes that the tree has been infested with balsam wooly aphid. Consider the situation reported by Schutt and Cowling (1985):

"During 1984, the forest disease situation in Europe grew worse. Symptoms are now found on almost every species of forest tree and on several shrubs and herbs."

Was the situation really so much graver in 1984 than it was in 1983, or is this an example of increased observer awareness? There needs to be developed statistical procedures for comparing observer ratings. Also, observers should be adequately trained to achieve a high degree of standardization.

THE MAJOR APPROACHES TO THE STUDY OF THE EFFECTS OF ATMOSPHERIC DEPOSITION

Following an analogy with medicine and public health, we propose two major conceptual approaches to the study of the effect of atmospheric deposition on forests:

- (1) The epidemiological approach, and
- (2) The physiological approach.

The epidemiological approach is characterized by broad surveys of forest condition and a search for patterns of condition that may be related to patterns in other aspects of the environment including atmospheric deposition. The physiological approach is characterized by more focused studies on the effects of environmental states on the well-being of individual trees. The general research strategy is for the epidemiological studies to uncover patterns of condition which then suggest particular hypotheses to be tested in a physiological study. The results of the physiological study must then be projected over an entire forest system to reconstitute the pattern of forest condition. This reconstitution is usually achieved through a model of the forest system, most commonly through the use of a tree and stand dynamics model (Figure 1). It is important to remember that scientists with different research styles will implement the different components of the overall strategy. We need to complete one cycle to guide in the design of future research at all levels.

In both approaches we need a control. In epidemiological studies a control is the mechanism for the elimination of confounding variables. This usually involves comparison of the patterns of condition in forests that have varied amounts of atmospheric deposition.

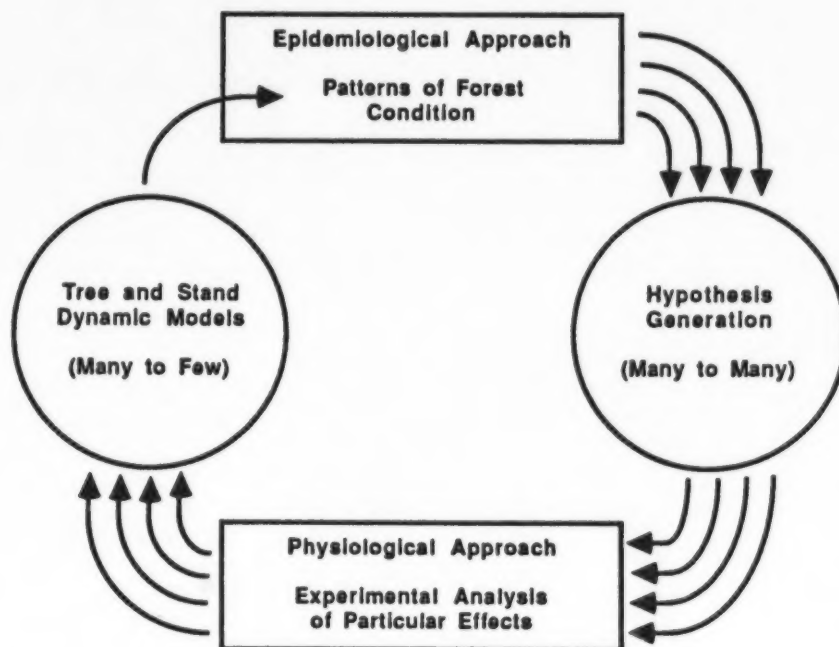


Figure 1.

This means that we must compare forests that are in different locations, compare the same forest at different times, or both. It is impossible to compare two forests that are equal in all respects except the amount of atmospheric deposition. Confounding variables are always present and their effects may overwhelm or mask the effect of atmospheric deposition. Therefore, the control in epidemiological studies consists of accounting for the other variables. In physiological studies consideration of control is more apparent and equally important. Some trees receive no treatment effects but are otherwise treated in just the same manner as those which do receive the treatment effect. Nonetheless, controls may require some thought as to the choices. For example, in a simulated acidic deposition experiment, we must establish which pH is to be used as the control. We certainly would not want to use a pH of 7. Should we use the average of rainfall over the U.S. or over the range of the experimental species? These questions often require more than casual thought.

THE EPIDEMIOLOGICAL APPROACH

As a practical matter, the condition (however measured) of any two forests or stands is likely to be corre-

lated to some degree. The amount of correlation depends a great deal on how close the two are in space and time. Forests far from each other may be quite uncorrelated; but this cannot be assumed out of hand. Thus different forests are not generally independent samples. This means that ordinary statistical methods are not suitable and that the techniques of time series analysis must be brought to bear on any epidemiological style investigations of forest condition. The term "time series analysis" refers to a body of (rather sophisticated) statistical methods for dealing with systems that are correlated through time. Similarly, there is a newer and less comprehensive body of methods for analyzing "spatial series" of systems correlated through space (Ord 1979). (For a variety of reasons spatial series analysis is technically more difficult than time series analysis.) The use of ordinary statistical methods on time series data constitutes one of the more frequently seen major blunders in the published literature.

Maps

An important first step in analyzing epidemiological data is to produce maps which serve to organize information and act as a reminder of the spatial patterns of dependency that can exist in the different systems being studied. Generally, maps that show aerial extent like in political regions provide little assistance by themselves. Maps that show the distributions of values of forest condition over an area (i.e., have isopleths of condition) are far more valuable. These maps must be accurate. Usually only a few points will be known and the rest interpolated. Frequently the value of these "known" points are the result of estimates which are subject to some error. Such sources of error must be quantified to establish the accuracy of the map.

Epidemiological Studies of Growth

There are many reasons why growth is the most commonly used index of forest condition. Historically, apparent declines in growth have triggered much of the concern about the effects of atmospheric deposition on forests.

Growth of forest trees is studied by two major methods:

- (1) Remeasurement
- (2) Tree ring analysis.

These two methods are complementary because both work to establish overall patterns of forest tree growth in space and time. These patterns become the objects of further research as their causes are sought.

It is difficult to locate study plots of trees using either method. There are two possible methods for locating study sites: Random sampling and sampling that is proportional to perceived threat. Scientifically, plots should be randomly placed within a large study forest or region. However, from a risk assessment point of view, we must consider the "leading indicator" forests to search out "hot spots" of damage and place plots in these locations. If the second method is used, it is crucial to keep in mind that extrapolation to other areas or to a region may not be scientifically valid.

Growth may be measured in many ways including radial, basal area, volume, and height growth. Each method has its advantages and disadvantages. Basal area growth is probably the most common method.

Growth of an individual tree is a function of both age and time regardless of the method used. As with any essentially demographic endeavor, these two variables are related but not identical. We are proposing a standardized method of plotting raw data from either tree ring or remeasurement studies. This method uses a three dimensional graph which plots growth directly as a function of age and time for each individual tree in a study area. The shape of the surface produced by such a plot gives valuable preliminary information about the regularity of the data and the patterns contained within it. We emphasize again how important it is in any study to plot the raw data as a first step in the analysis.

Remeasurement Studies

Certainly the most straightforward way to determine growth rates in trees is to repeatedly measure individual trees through time. The disadvantages with this method are that the trees must continue to exist through time and that the series can be no longer than the length of the study. In practice, it is unusual to find a series that is over 30 years old. On the other hand, most putative pollution events are of recent origin. An advantage of this method is that collateral information such as stand density can be obtained at the same time. This is not the case with tree ring studies.

Tree Ring Studies

Dendrochronology and dendroclimatology are studies that help us understand the effects of atmospheric deposition on forests. Earlier simplistic studies were unsuccessful and have caused some to give up on the technique prematurely. However, recent work using new and sophisticated time series methods have a brighter future (Cook 1985).

Trees are natural data recorders (Creber 1977) and a host of factors affect the pattern of ring widths through time including atmospheric deposition. We need to extract the effects of the pollution problem out of the effects of other factors.

Each of these methods of study have a diminished ability to deal with the ends of series. If we have a record 200 years long, the methods work much better in the middle of the series than in the last 15 years. Unfortunately, this is exactly where we expect evidence of pollution effects to occur. We can see that tree ring studies must be complemented with remeasurement and stand history studies to compensate for this weakness.

Other data may be contained in tree rings besides their width. Density and detailed intraring patterns of early and late wood are currently under intensive investigation. Also various chemical elements are contained in the rings and the variation in their concentrations is a potential indicator of the amount and type of deposition. Most of the problems with this approach are technical. In particular, the question of translocation of elements between rings can only be answered by careful experimentation. If the technical aspects of this approach can be resolved successfully, the extension of statistical methods developed for width data will be relatively straightforward.

Climate and Weather: Famous Natural Factors

Climate and weather constitute the largest single constellation of natural factors affecting forest condition. Perhaps the most significant aspect of these factors is the number of scales in space and time over which they can vary. Actually the division between weather and climate is already a distinction of time and space scales. Climate occurs over longer periods of time and larger areas. Weather is more local in both space and time. Both local and global aspects are important in the analysis of atmospheric deposition.

For example, local rainfall can be tremendously variable (Eynon and Switzer 1983), especially in areas of to-

pographic diversity. In some areas rainfall is even and relatively continuous and in others it can be highly episodic. Snow and other climatic effects can also be episodic or continuous. This diversity leads to a class of serious statistical sampling problems: In sampling rainfall for acidity, for example, should the sampling be periodic or episode induced? These two methods are each appropriate for different rainfall regimes, but may not be comparable. We have seen one study in which it was proposed to use one method in one state and the other in another. Much more attention must be given to this design issue.

A similar problem arises when one considers the response of some measure of forest condition to weather. Tree and stand response may be continuous or threshold and may therefore demand different sampling methods. In general, it is important to concurrently measure both a forest response to weather and climate along with weather and climate themselves. There is the possibility of a non-linear relationship between forest condition and measure of weather.

The global or large scale pattern of wind and rain is also exceedingly complex. Here we are most concerned with secular trends over the last few decades and over large forest regions. There is some evidence of decade scale trends in weather, especially rainfall and minimum winter temperatures, that correspond closely in time with the onset of potential atmospheric deposition. The nature of these trends and of the response of forest condition to them (whether continuous or threshold) must be well understood before the effects of atmospheric deposition can be quantified.

Pollution: A Famous Human Factor

The diversity of things deposited from the atmosphere onto forests is staggering. These substances include literally hundreds of chemical species, dust, soot, and so forth. With this many chemical species possible, the number of interaction effects is potentially in the many thousands. This is worth keeping in mind because any two species taken together may be very nonadditive in their effects on forest condition.

An important aspect of any deposited substance is its spatial and temporal pattern. Comparison of patterns of deposition with patterns of condition using spatial models is a much more powerful test of the potential relationship than comparing a series of points. One of the most promising areas in ADIF research is the development of spatial models of patterns of deposition and condition using new spatial series modeling methods and statistical

methods such as kriging. Most of these methods were developed by statistical geographers and geophysicists and are now just beginning to be applied to atmospheric deposition research.

Particular pollutants are often characterized by the spatial distribution of their sources. Some pollutants are characterized as point source pollutants such as are emitted from a particular power plant. Others are called nonpoint source pollutants as from automobiles. Models of these two types of systems may help us picture the spatial pattern of pollution which can then be compared to patterns of forest condition.

Rainfall: An example of a combination of natural and human factors

Rain exemplifies the complexity of determining what is a natural and what is a human factor. It is both:

1. A natural factor affecting growth of trees directly.
2. A major source vehicle for atmospheric deposition.

The interactions between these two may be complex. For example, suppose we consider varying both the amount of rain and the pH of the rain. Holding either constant and varying only one might produce simple results. But the overall response of forest condition to the combination is not known. In other words, a three-dimensional graph of forest condition as a function of amount of rain and pH would produce a surface which is the response. We do not know what this response surface would actually look like.

Rainfall also has long-term complex effects such as its effect on the water table in a given region. But clearly the water table is also greatly affected by human use.

Hypothesis Generation

Hypotheses about the specific mechanisms of action of particular factors on aspects of trees and forests can come from many sources including general scientific knowledge, common sense, and imagination. But certainly an important source of hypotheses are the patterns of forest condition generated by the epidemiological style studies. If a pattern of forest condition is found in space or time, it can be compared to patterns of various factors in the environment to generate new hypotheses.

It may be convenient to classify the factors which could ultimately affect forest condition. For example, if

a decline in growth was detected over a region, many possible factors would have to be considered in attempting to account for the decline.

I. Natural factors.

- A. Present and known. These are the factors assumed to affect all forests to some degree such as age or climate.
- B. Present and unknown. These are natural factors currently undiscovered by science. Unknown mechanisms of root competition might be an example.
- C. New. These are factors which, although natural, have only been affecting the trees and forests recently. A newly invaded disease organism might be an example.

II. Human Factors.

- A. Present and known. Factors such as logging.
- B. Present and unknown. These would include pollutants whose effects are not known and not considered. Low level, but chronic, factors might be a common case here.
- C. New. Factors that have appeared in the environment only recently which may affect it. Many kinds of atmospheric deposition fall under this category.

Hypothesis generation is especially important in the area of unknown factors. Progress will not occur unless many new hypotheses are generated and tested.

THE PHYSIOLOGICAL APPROACH

The physiological style of research enjoys great success in many areas. In the study of the effects of atmospheric deposition on forests, it takes the form of examining a particular effect in a controlled experimental design and characterizing physiological processes.

For the purposes of these kinds of studies, the forest can be thought of as consisting of a large number of compartments of various sizes which divide up the dynamic structure of the forest. Thus the compartments are bite sized pieces of reality which can be subjected to experimental analyses. However, for the purpose of the experimental analysis of causation, these compartments are assumed to be independent of one another.

Compartments are often the various parts of a tree such as the crown, or leaves. They can also be components of the soil, sets of competing species, or many other aspects of the forest ecosystem. Thus a study might be carried out on the effect of ozone on foliage health in a particular species while another study could be carried out on the effect of ozone on the formation of ectomycorrhizae in the same species. The compartment approach assumes that there is no important interaction between foliage health and the formation of ectomycorrhizae.

Once a potential effect and a particular compartment has been identified, from a statistical point of view it is relatively straightforward how to proceed. The problems of design and statistical analysis for physiological style research are much better understood and are generally well known. The first rule is to consult a statistician before beginning the experiment. Beyond that the many standard texts and review articles contain the necessary information.

Many experimental designs lend themselves to analysis of variance; and here the standard advice of randomize and replicate must be emphasized as strongly as possible. Despite the fact that this is a well known area, many workers still confuse replication with subsampling (Hurlbut 1984). Many workers also do not fully exploit the logical structure of the experimental design in setting up the analysis of variance. And pretreatment techniques which can be important in field experiments ought to be considered more frequently.

Simulated acid rain studies are an important general technique. Concern in the design must be focused on the choice of pHs to be used and on the mechanism by which the "rain" is physically applied. Standardization of the second has yet to be accomplished, but the work of the pesticide researchers might profitably be considered here.

From the analysis and design point of view, the ideal approach is a dose-response study analysis using standard statistical methods (e.g. probit analysis). The remaining concerns overlap into risk assessment:

1. Low dose extrapolation. Often it is necessary to use higher doses in the experiment than occur in nature to get definite results. The dose-response curve must then be extrapolated to lower values for application to nature. Some statistical procedures have been developed for this.
2. Chronic long-term extrapolation. Often an experimental procedure only lasts a mere fraction of the

life of a tree. Therefore results need to be extrapolated over longer periods and often over older ages as well since many experiments use only seedlings.

MODELING TREE AND STAND DYNAMICS

Once a particular experimental analysis has uncovered the effect of a given cause, it is necessary to evaluate the importance of that cause in creating the pattern of forest condition that has been observed. In other words, we need to see if this particular mechanism actually is operating at a significant level in nature and can contribute significantly to the reconstitution of the pattern discovered through epidemiological investigations.

The only real method that exists for such evaluation is modeling of the dynamics of trees and forests. In this sense, a model is a mathematical method for "balancing the books" on forest growth or some other measure of condition. There are numerous inputs to the model but only one "balance", namely the actual pattern of forest condition. A model acts as a summary of two kinds of knowledge. First, it encapsulates the general biological principles that apply to tree and stand dynamics. Second, it summarizes the actual data known about a particular system. There is a long tradition in forestry and systems ecology of such models. The methods that have been developed constitute a great resource for workers in atmospheric deposition. In forestry, in particular, these are known as "growth and yield" models.

As shown in Figure 1, models of tree and stand dynamics synthesize the information obtained from experimental studies in such a way as to evaluate how the cause-and-effect mechanisms studied account for the pattern of forest condition. We are convinced that progress in the solution of the atmospheric deposition problem will only come through repeated iterations of the cycle illustrated in the figure. In particular, an early attempt to complete one cycle is crucial to planning future work. In other words it is important to evaluate the data and knowledge that we have as it is being acquired rather than waiting until the end. This means that we can learn from experience and apply new knowledge. Science is an iterative process.

Early modeling is also important. In the absence of specific atmospheric deposition effects, the model produced is a null model of tree and stand dynamics. This accounts for their behavior in the absence of any atmospheric deposition. Such models are necessary to realistically determine if there is any atmospheric deposition effect.

Finally, modeling is fundamental to any efforts at risk assessment. The processes implied by any particular study must be projected over entire forests and regions to establish their impact on condition and hence their ultimate impact on forest and land value.

In summary, modeling is a method for quantifying atmospheric deposition on forest condition. This is the method we will use to synthesize our knowledge into a usable package. We must exert effort toward synthesis to make it a part of our acidic deposition solution. It will not come about merely by accident or simply because a conference is held.

ACKNOWLEDGEMENTS

This paper arose from my thoughts about work done jointly with Tommy Dell and Paul Van Deusen of the Southern Forest Experiment Station. As part of the Vegetation Survey of the Forest Response Program, we ran a "Distributed Seminar" or "Seminar by Mail" in which selected works were mailed out weekly to a team of 13 forest biometricians, statisticians and quantitative ecologists. These 13 were chosen both for expertise and diversity as part of a philosophy of "replicating statisticians" in an area where there are no obvious "canned" approaches. Over a period of 8 weeks, there were 27 articles, 13 proposals, several maps and associated materials sent out. The team members responded each week by reviewing these documents, proposing alternative ideas and methods, and suggesting areas for future work. While I take full responsibility for the conclusions presented here (and indeed some of the participants would strongly disavow them), it is certainly the case that they stimulated me greatly.

In addition to Tommy Dell and Paul Van Deusen, the participants were: Robert L. Bailey, Bruce E. Borders, Janice A. Derr, William L. Hafley, Carl W. Mize, J. Keith Ord, Robin Reich, Marion Reynolds, Michael G. Shelton, Robin A. J. Taylor, Michael Wade, William G. Warren, and Lee C. Wenzel. Thank you all.

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